5-15-2001

Controls on Floc Size in a Continental Shelf Bottom Boundary Layer

Paul S. Hill
Dalhousie University

George Voulgaris
University of South Carolina - Columbia, gvoulgaris@geol.sc.edu

John H. Trowbridge

Publication Info

Published in *Journal of Geophysical Research*, Volume 106, Issue C5, 2001, pages 9543-9549.
Hill, P. S., Voulgaris, G., & Trowbridge, J. H. (2001). Controls on floc size in a continental shelf bottom boundary layer. *Journal of Geophysical Research, 106* (C5), 9543-9549.

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 106, NO. C5, PAGES 9543–9549, MAY 15, 2001

Controls on floc size in a continental shelf bottom boundary layer

Paul S. Hill
Department of Oceanography, Dalhousie University, Halifax, Nova Scotia, Canada

George Voulgaris
Marine Science Program, Department of Geological Sciences, University of South Carolina, Columbia

John H. Trowbridge
Department of Applied Ocean Physics and Engineering, Woods Hole Oceanographic Institution
Woods Hole, Massachusetts

Abstract. Simultaneous in situ observations of floc size, waves, and currents in a continental shelf bottom boundary layer do not support generally accepted functional relationships between turbulence and floc size in the sea. In September and October 1996 and January 1997, two tripods were deployed in 70 m of water on the continental shelf south of Woods Hole, Massachusetts. On one a camera photographed particles in suspension 1.2 m above the bottom that had equivalent circular diameters larger than 250 μm, and on the other, three horizontally displaced acoustic current meters measured flow velocity 0.35 m above the bottom. The tripods were separated by ~150 m. Typically, maximal floc diameter stayed relatively constant, around 1 mm, and it showed a dependence on turbulence parameters that was significantly weaker than that predicted by any model that assumes that turbulence-induced stresses limit floc size. Occasionally, when waves and currents generated intense near-bed turbulence, flocs were destroyed. These precipitous decreases in maximal floc size also were not predicted by conventional models. The correlation in time between episodes of floc destruction and elevated combined wave-current stresses provides the first quantitative support for the hypothesis that floc size throughout bottom boundary layers can be controlled by breakup in the intensely sheared near-bed region. These observations demand a reassessment of the forces limiting floc size in the sea, and they indicate the potential for significant simplifying assumptions in models of floc dynamics.

1. Introduction

Particles in the aqueous environment transport carbon and adsorbed contaminants [*Gustafsson et al.*, 1998], feed myriad creatures [*Snelgrove and Butman*, 1994], foul waterways [*Marine Board*, 1985], affect optical properties [*Campbell and Spinrad*, 1987], and store a valuable environmental record [*McCave et al.*, 1995]. Understanding particle transport has been the goal of ocean scientists and engineers for decades. Particles in suspension are packaged predominantly in porous agglomerations called flocs [*Kranck and Milligan*, 1992]. This repackaging of particles affects their transport rate profoundly [*McCave*, 1975], yet understanding of the controls on floc size remains rudimentary [*Dyer*, 1989; *Hill*, 1998].

Repackaging of particles into flocs affects numerous industrial processes that employ gravitational settling to remove solids from suspension. Disciplines such as wastewater treatment and mineral processing therefore share a long history of research into the forces that limit floc size [*Hunt*, 1986]. Given the vigorous stirring typical of industrial sedimentation tanks, focus has been on the effect of turbulent shear in limiting floc size. Models from these fields predict that maximal floc size scales as ε^{-b}, where ε is the turbulent kinetic energy dissipation rate in the fluid. Proposed values of the exponent b range from 0.25 to 1, depending on the mechanism of breakage by turbulence-induced stresses. Laboratory studies in vigorously stirred tanks generally support these theories. Therefore oceanographers have adopted the assumption that small-scale turbulence-induced shear limits floc size [*Jackson*, 1995; *Hill*, 1996; *Ruiz and Izquierdo*, 1997], but data to test in situ this assumption are lacking.

Several sets of observations suggest that under energetic conditions, turbulence can limit floc size in bottom boundary layers [*Kranck and Milligan*, 1992; *Luettich et al.*, 1993; *Eisma et al.*, 1996; *Berhane et al.*, 1997], yet these studies lack the type of measurements required to evaluate the predictive ability of various proposed relationships between maximal floc size and turbulence. Specifically, previous studies have not measured waves and currents well enough to produce accurate estimates of the boundary shear stress, which is linked to ε in bottom boundary layers [*Heathershaw*, 1979; *Luettich et al.*, 1993]. This gap between theory and observation was bridged recently during the Coastal Mixing and Optics experiment sponsored by the Office of Naval Research, during which simultaneous measurements of floc size, waves, and currents were made for the first time in a continental shelf bottom boundary layer. The

Paper number 2000JC900102.
0148-0227/00/2000JC900102$09.00

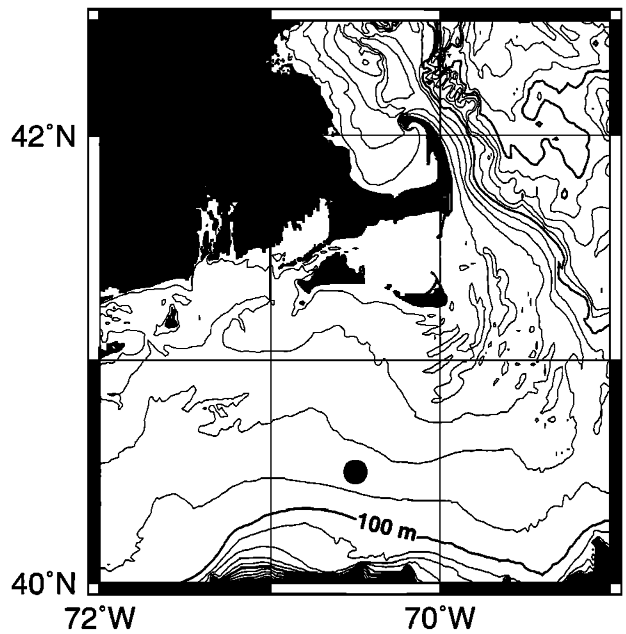

Figure 1. Coastal Mixing and Optics experiment site map. The large dot at 70 m water depth marks the position of the tripod deployments.

goal of this work is to use these data to conduct a rigorous assessment of the in situ effect of turbulence on floc size.

2. Methods

From August 1996 to June 1997, two tripods were deployed at 40°29.40′N, 70°30.25′W in 70 m of water on the continental shelf 100 km south of Martha's Vineyard, Massachusetts (Figure 1). The first carried a camera designed to photograph particles in suspension. The second carried a suite of acoustic flow meters that measured wave and current velocities at a range of heights above bottom. The two tripods were ~150 m apart.

A 35 mm camera equipped with a 50 mm lens and a 250-image frameback was used to photograph particles. The field of view was a 25 cm wide by 37 cm high by 2.5 cm thick slab of fluid 76 cm away from the camera and 120 cm above the seabed. The camera was programmed to take a picture every 8 hours. Images were acquired in August, September, and October 1996 and January 1997. The images were developed as slides and transferred digitally to Kodak PhotoCDs at a resolution of 2048 by 3072 pixels.

Particle size analysis was performed with Media Cybernetics Image Pro Plus 3.0 software. Images were processed in batches with two macros. In the first macro, images were imported at full resolution. Then a two-pass, 3 × 3, strength 5 sharpen filter was applied to enhance fine detail and refocus any blurred parts of the image [*Russ*, 1995]. Filtered images were converted from color to gray scale and then saved as tiff files. The second macro opened the newly created tiff files and then positioned an "area of interest" box relative to a bolt used as a calibration object in each image. The 7.18 cm wide by 4.81 cm high box was identical for all images. Next a cumulative distribution plot of gray scale in the area of interest within an image was generated. This plot portrays the fraction of the total pixels that have gray scales less than or equal to a given value. The integral gray-scale value marking the whitest 6% of all pixels was determined. The gray-scale value marking a particle edge was defined as the above value plus 5 gray-scale units. This arbitrary and objective method was developed by empirical comparison of an operator-selected threshold for edge detection with a variety of objective machine-determined thresholds. Each gray-scale image was converted to binary by calling all pixels with gray scales above the threshold white and all other pixels black [*Russ*, 1995]. Then particles with areas in the range of 0.393–15.83 mm^2 were outlined and counted. This range incorporates all particles large enough to show insignificant spatial variability within the analysis box. It corresponds to equivalent circular diameters of 0.707–4.489 mm. A full watershed split was then run to divide any apparently overlapping particles [*Russ*, 1995] and then particles were reoutlined and counted. In images containing particles, areas for all particles were stored in a database. Images without particles were recorded in the database as having no data.

Because particle areas were neither normally nor lognormally distributed for more than half of the images, $d25$ was used as a proxy for maximal floc diameter. This parameter is found by calculating the frequency distribution of particle areas within the analysis box of an image. The equivalent circular diameter of the particle area marking the boundary between the lower three quarters and upper one quarter of the particle areas is $d25$.

Turbulent kinetic energy dissipation rate in a boundary layer varies as the fluid shear stress raised to the 3/2 power [*Heathershaw*, 1979]. In the presence of waves and currents, two shear stresses characterize the near-bed region. In the wave boundary layer, which extends only a few centimeters above the seabed, shear stress attains a maximum [*Grant and Madsen*, 1986]. Both waves and currents contribute to this maximal stress, so it is referred to herein as the combined wave-current stress τ_{wc}. Above the wave boundary layer is the current boundary layer where shear stress is due to the mean flow, with some enhancement due to the presence of waves [*Grant and Madsen*, 1986]. This shear stress is referred to herein as the mean stress τ_c, denoting the role of currents in setting its value.

Maximal floc size observed by the camera potentially was controlled either by the combined wave-current stresses encountered by flocs in the wave boundary layer (τ_{wc}) or by the mean current stresses within the camera's field of view (τ_c). Which stress controlled floc size depends on the rate at which turbulent eddies were moving flocs around in the bottom boundary layer relative to the rate at which flocs were forming [*Hill and Nowell*, 1995]. If flocs were forming rapidly, then maximal floc size should have been set by the turbulent kinetic energy dissipation rate in the vicinity of the floc. In this case, conventional models of floc breakup [*Hunt*, 1986] predict that maximal floc size should scale as the mean stress τ_c raised to a power between $-3/8$ and $-3/2$. If vertical turbulent transport of flocs through the boundary layer out-paced floc formation, then maximal floc size should have been set by the maximal turbulent kinetic energy dissipation rate that flocs encountered. In this case, maximal floc size should scale as combined wave-current shear stress, τ_{wc} raised to a power between $-3/8$ and $-3/2$. In the present study, functional relationships between both maximal floc size and combined wave-current shear stress in the boundary layer and maximal floc size and mean shear stress in the boundary layer were examined.

Wave and current data were gathered with three horizontally displaced acoustic Doppler velocimeters (ADV) mounted on a 8 m tall tripod [*Voulgaris and Trowbridge*, 1998]. The sensors were positioned vertically to measure the three-dimensional (3-D) velocity field at 35 cm above the seabed [*Voulgaris et al.*, 1998]. The sensors were positioned horizontally in a triangular configuration, with a distance of 220 cm along each leg of the triangle. This configuration allowed implementation of a new technique for making direct estimates of Reynolds stress in the presence of waves [*Trowbridge*, 1998]. The ADV sensors measure the three components of flow with a resolution of 1 mm s^{-1}. Sensors were synchronized and sampled every hour for a 9.6 min period at 25 Hz.

The mean characteristics of the flow were estimated by averaging over each 9.6 min data collection period. Wave orbital velocity for each period was defined as $U_b = \sqrt{2(\langle u\rangle^2 + \langle v\rangle^2)}$, where wave-induced variances in downstream and transverse directions, denoted $\langle u\rangle^2$ and $\langle v\rangle^2$, respectively, were defined as the variances in the frequency range 0.03 to 0.25 Hz. The wave period was calculated as the reciprocal of the weighted mean of the frequency bins in the 0.03–0.25 Hz range, with the weighting factors equal to the energy in each bin. The angle of wave approach was defined as the angle of maximum variance. Accurate estimates of mean flow shear stress τ_c for each ADV pair were generated using the Reynolds-stress method [*Voulgaris and Trowbridge*, 1998]. A modified method that uses differences between the velocities measured by two sensors was used to decorrelate the wave-induced and turbulence signals [*Trowbridge*, 1998; *Voulgaris et al.*, 1998]. Mean current shear stress was set equal to the mean of the estimates from the three pairs of ADVs.

Because of the absence of measurements in the wave boundary layer, which are exceedingly difficult to make, combined wave-current shear stress τ_{wc} was estimated with a wave-current interaction model [*Sleath*, 1991]. Mean stress, mean velocity, wave velocity, and wave period were used as inputs to the model to estimate iteratively the combined wave-current shear stress τ_{wc} and bottom roughness.

The slopes of the functional relationships between the logarithm of maximal floc size and the logarithms of the two shear stresses were determined with Model II regression, which is appropriate when both variables in a regression are random variables [*Sokal and Rohlf*, 1981]. Because floc size and stress have different dimensions, geometric mean regression was employed. Logarithms of $d25$ and stress were transformed to have zero means and standard deviations of one. The slopes of the principle axes of these standardized variables are estimates of the exponents in the power laws relating maximal floc size to mean and combined wave-current shear stresses. Confidence limits on the slopes were calculated by assuming that the standard errors of the geometric mean regression slopes are equal to the standard errors of the slopes yielded by model I simple linear regression [*Sokal and Rohlf*, 1981].

3. Results

Two different types of images acquired by the camera challenge conventional ideas regarding controls on floc size in the sea (Plate 1). The first type, comprising 154 of 164 photographs for which ADV data were available, shows that over a wide range of maximal and mean shear stresses, flocs maintained relatively uniform diameters (Figure 2). The second type, represented by the other 10 images, shows that flocs were occasionally reduced to sizes not resolvable by the camera. The lack of visible flocs in these images suggests that diameters were reduced to <0.25 mm. This two-state system in which $d25$ is either of order 1 mm or <0.25 mm is not predicted by any model that assumes that turbulence alone limits floc size in the sea. Such models predict that a continuous range of maximal floc sizes varying systematically with stress should have been observed in this study.

When flocs were visible, $d25$ was in the range of ~1–3 mm and depended only weakly on the inverse shear stress as $d25 \sim \tau_{cw}^{-0.26\pm0.04}$ and $d25 \sim \tau_c^{-0.18\pm0.03}$ (Figure 2). Exponents are shown with 95% confidence intervals, indicating that at that confidence level both exponents relating $d25$ to stress are significantly smaller than any existing model predictions that link maximal floc size to small-scale turbulence-induced shear. The minimum absolute value predicted by such models is 0.375 [*Hunt*, 1986; *Alldredge et al.*, 1990]. Apparently, in images with visible flocs, small-scale turbulence-induced shear did not limit floc size in a way predicted by theory.

Substantial reductions in floc size primarily occurred during periods of elevated combined wave-current shear stress τ_{wc}. The 10 images with no resolvable flocs had associated combined stresses that were large relative to those associated with the other 154 images (Figure 3). Combined wave-current stresses for images without flocs exceeded 0.1 Pa. The correlation between floc disappearance and elevated mean shear stress τ_c was weaker than the correlation for combined wave-current shear stress. Mean current stresses associated with images lacking flocs overlapped substantially with stresses from images with flocs (Figure 3). These qualitative assessments of controls on floc breakup were evaluated statistically by performing a chi-square test [*Dunn*, 1964] of the hypothesis that the probability of finding images without flocs when shear stress was less than or equal to its median is equal to the probability of finding images without flocs when shear stress was greater than its median. This test indicates that the null hypothesis can be rejected at the 95% confidence level ($p < 0.005$) for combined wave-current shear stress but that it cannot be rejected ($p < 0.1$) for mean shear stress. These results support the hypothesis that flocs were destroyed predominantly in the wave boundary layer but only when stresses exceeded 0.1 Pa. The marked size reduction that occurred indicates that some breakup mechanism became active only under energetic conditions. The obvious candidate is floc splitting by small-scale turbulence-induced fluid shear [*Hunt*, 1986; *Alldredge et al.*, 1990].

4. Discussion

Although the lack of any resolvable flocs in some images most likely indicates floc breakup in the bottom boundary layer, other factors may explain the disappearance of flocs. An alternative explanation is that resuspended, unflocculated bottom sediment may obscure flocs when boundary shear stresses are high [*Heffler et al.*, 1991]. Disaggregated grain size analysis [*Milligan and Kranck*, 1991] of sediment sampled from a tripod foot revealed a modal diameter of ~80 μm for sediments at the site. The critical erosion shear stress for quartz particles this size is ~0.1 Pa [*Miller et al.*, 1977], suggesting that resuspension may contribute to the altered appearance of many of the images taken at stresses above 0.1 Pa. Because silt and clay are abundant in bottom sediments at this site, however, single grains are not likely to have been eroded from the bed. More likely, these cohesive sediments would have been resuspended

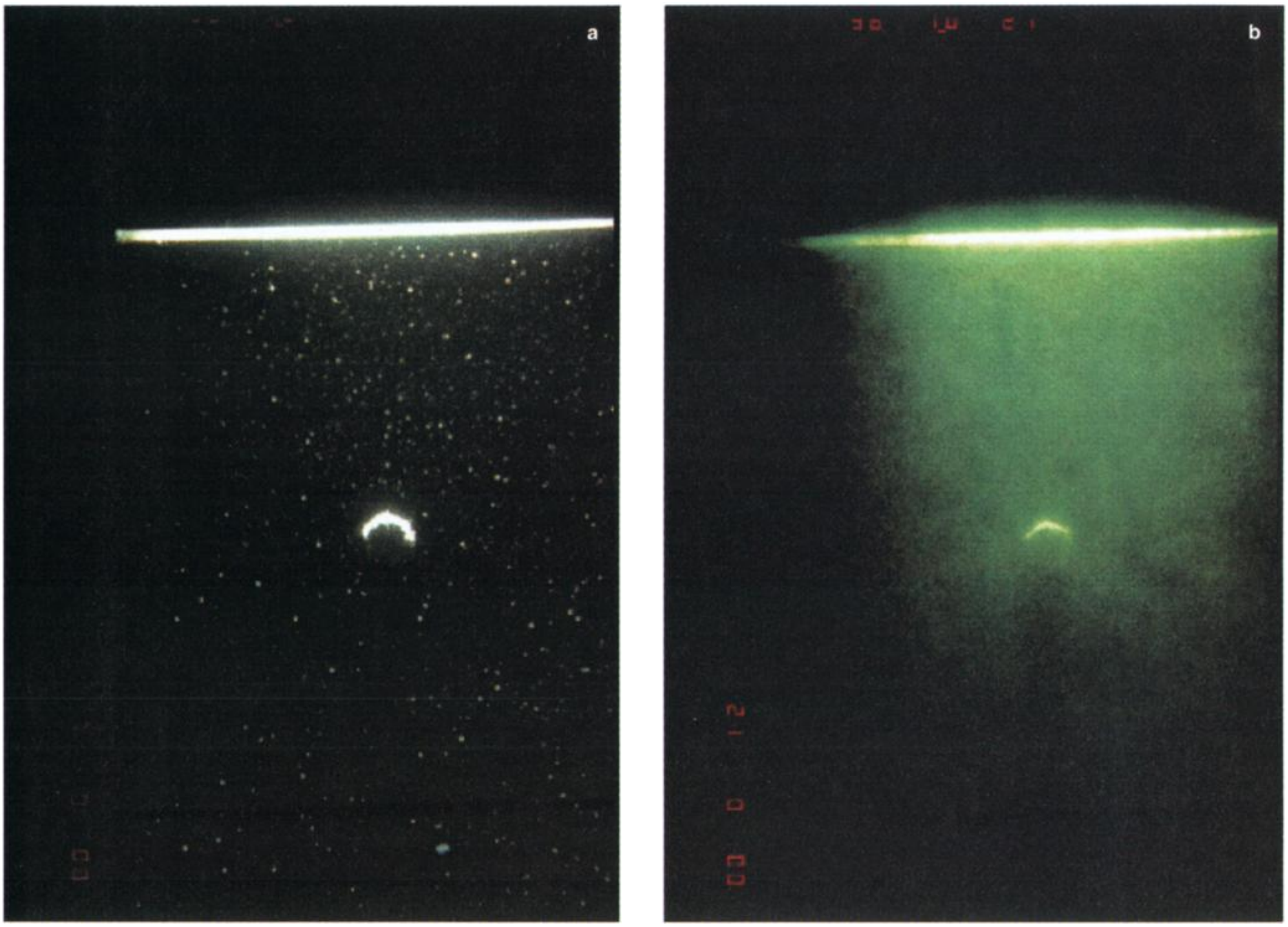

Plate 1. Examples of two types of image captured by the camera. The bright line at the top of each image is the flash. The crescentic object in the middle of each image is the upper edge of a 1.90 cm diameter bolt head that was positioned in the field of view for spatial calibration. Most images resembled Plate 1a. Large flocs of ~1 mm diameter populated these images. Images like Plate 1b only occurred when maximal shear stress exceeded 0.1 Pa. No flocs were resolvable in these images, suggesting that turbulence had reduced floc sizes to below 0.25 mm.

as flocs or aggregates [*McCave et al.*, 1995; *Agrawal and Traykovski*, this issue]. Thus the fact that in the 10 "broken floc" images no flocs are visible but the bolt head is (Plate 1) supports the hypothesis that no flocs were present. A second alternative explanation for the disappearance of flocs is that during storms, parcels of water lacking flocs are advected through the study site. For all high-energy events during this study, storms advected water from the east. Because bottom sediment grain size actually coarsens to the east [*Twichell et al.*, 1987], this hypothesis lacks support. Thus floc breakup remains the most viable explanation for why some images lack resolvable flocs.

Observations of particle size in the diameter range 5–500 μm made with a LISST-100 laser diffraction particle sizer mounted on the camera tripod [*Agrawal and Traykovski*, this issue] bolster the hypothesis that the lack of resolvable flocs in some images arises from floc breakup. In September 1996, Hurricane Edouard passed within 80 km of the tripod site [*Dickey et al.*, 1998]. Just before the arrival of the hurricane, flocs were visible, and the LISST-100 sensed low particle concentrations and large particle sizes. During the hurricane, flocs disappeared and then reappeared as stress decreased. During the same interval, particle size sensed by the LISST-100 started large, then decreased, and then increased again as stress relaxed. This evolution of size is counter to that expected from resuspension, during which smaller particles should be suspended first and sink last. Floc breakup and reformation are the most obvious mechanisms for producing this evolution of particle size.

The significantly weaker than predicted dependence of floc size on boundary shear stress indicates that turbulence may not limit floc size at low-to-moderate shear stresses. This finding runs counter to the widely accepted hypothesis that turbulence is solely responsible for limiting floc size in the sea [*Jackson*, 1995; *Hill*, 1996; *Ruiz and Izquierdo*, 1997], yet this hypothesis is consistent with the only other study to examine systematically the relationship between marine floc size and turbulence. In a laboratory study, *Alldredge et al.* [1990] introduced five different types of flocs into an oscillating grid turbulence tank. Maximal ε in the tank was $>10^{-4}$ W kg^{-1}, which is large relative to typical ε in the ocean [*Alldredge et al.*, 1990]. That three of five floc types experienced no disruption in the tank was therefore surprising. Only fragile diatom flocs suffered any breakage, and many of these remained intact. Furthermore, three floc types in the Alldredge study showed no significant dependence on ε over the large range in the tank. For another floc type in the Alldredge study, maximal floc size scaled as $\varepsilon^{-0.11}$, whereas the weakest predicted dependence scaled as $\varepsilon^{-0.25}$. Only one floc type yielded a power law dependence of maximal floc size on ε that was not significantly different from theory.

Alldredge et al. [1990] proposed microbial degradation, bacterial solubilization, and animal grazing as other mechanisms for limiting floc size in the sea. However, reconciling these mechanisms with the observed uniformity of floc size at the Coastal Mixing and Optics site over the period of midsummer to midwinter, during which biological processes likely varied significantly, is difficult. Another proposed mechanism for limiting floc size is disruption by stresses exerted on flocs as they sink [*Hill et al.*, 1998]. Although these stresses are not large, scale analysis shows that at the relatively low values of turbulent kinetic energy dissipation rates in the ocean they often exceed turbulence-induced stresses.

In the late 1970s P. M. Adler [*Adler and Mills*, 1979; *Adler*, 1979] published a rigorous mathematical model of floc breakup that was unique in considering the roles of both sinking- and turbulence-induced stresses in limiting floc size. This work showed that below some critical shear, whose value depends on particle strength, shear ceases to limit aggregate size. It also showed that stresses induced by sinking always limit floc size. Thus, according to Adler's model, below some critical value, floc size ceases to vary with shear. Above that value, floc size decreases as shear grows. These predictions are more consistent with observations than are the predictions of models that assume that turbulence alone limits floc size.

The weak dependence of floc size on boundary shear stress found in this study is predicted neither by Adler's model nor by conventional models of floc breakup. This dependence may indicate that turbulence exerts some limited influence on floc size at stresses below the stress at which massive disruption, likely by turbulence-induced floc splitting, takes place. It also may be linked to resuspension of inorganic-rich bottom sediment, which tends to form smaller, denser flocs than organic-rich sediment [*Logan and Wilkinson*, 1990]. That some images with stresses above 0.1 Pa contain flocs also may reflect compositional variability in the suspension.

The correlation in time between episodes of floc breakup and elevated combined wave-current shear stress (Figure 3) indicates that floc size at the level of the camera 1.2 m above the seafloor is controlled by processes operating within the wave boundary layer a few centimeters above the seabed. These observations provide the first quantitative support for the longstanding hypothesis that near-bed turbulence limits floc size in bottom boundary layers [*Stow and Bowen*, 1980; *McCave*, 1985; *McCave et al.*, 1995]. Before accepting these observations as support for this hypothesis, evaluating whether mixing timescales are indeed smaller than aggregation timescales is important.

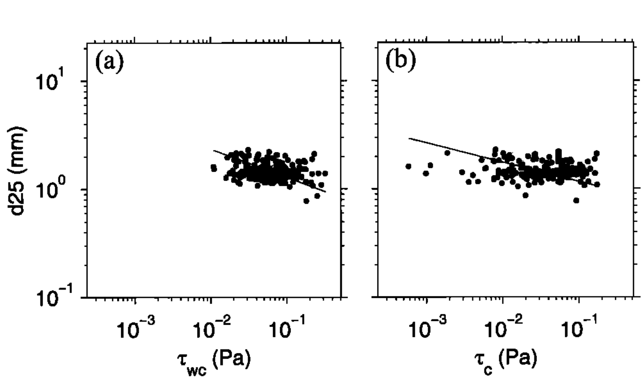

Figure 2. Plots of $d25$ versus shear stress. Maximal floc size, as characterized by the parameter $d25$, fell slightly as (a) maximal and (b) mean shear stresses grew. Model II regression of the log of $d25$ versus the log of the two shear stresses shows that $d25 \sim \tau_{cw}^{-0.25\pm0.04}$ and $d25 \sim \tau_c^{-0.18\pm0.03}$. These dependencies of maximal floc size on shear stress are significantly weaker than any prediction of models that assume that floc size is limited by small-scale, turbulence-induced stresses.

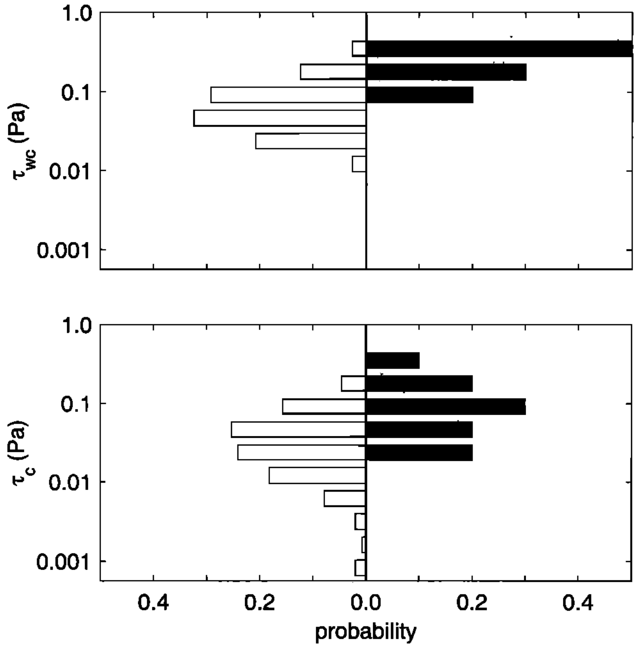

Figure 3. Frequency functions of maximal and mean stresses for images with and without flocs. Frequency functions for (right) images with no flocs had higher associated stresses than (left) images with flocs. (top) Overlap of combined wave-current stresses for images with and without flocs was substantially less than (bottom) the overlap of mean current stresses (τ_c, bottom), suggesting that floc breakup occurred predominately in the wave boundary layer where stresses were highest.

The timescale t_m required to cycle a particle through the near-bed region, up to the camera, and back again scales as $\kappa z/u_*$, where κ is von Karman's constant (0.4), z is camera height (1.2 m), and u_* is the shear velocity ($\sqrt{(\tau/\rho)}$) [*Hill and Nowell*, 1995]. Assuming that the shear stresses are ~0.1 Pa when flocs are destroyed and that fluid density ρ is 1025 kg m^{-3}, mixing times are ~50 s. When combined wave-current shear stress grows large enough to destroy flocs, a suspension will become unflocculated if the particles liberated from broken flocs are unlikely to reaggregate outside the wave boundary layer before being returned to it by turbulent mixing. Assuming that reaggregation occurs by scavenging of small particles by large flocs, estimating aggregation timescales with the floc photographs from this study is possible.

The timescale t_a for scavenging a type i particle by type j particles is [*Hill and Nowell*, 1995]

$$\frac{1}{[(\alpha_{ij}E_{ij}K_{ij})_{TS} + (\alpha_{ij}E_{ij}K_{ij})_{DS}]n_j}, \qquad (1)$$

where α_{ij} defines the number of particle contacts that result in sticking, E_{ij} defines the number of particle encounters that result in contact, K_{ij} defines the encounter rate coefficient between particles of types i and j, and n_j is the number concentration of type j particles. The subscripts TS and DS refer to two mechanisms for bringing particles together: turbulent shear and differential settling.

The terms α_{ij} and E_{ij} are poorly constrained and are likely significantly less than one [*Hill*, 1992; *Li and Logan*, 1997]. To calculate the smallest possible aggregation time, however, their values for this exercise are assumed equal to unity. If aggregation times exceed mixing times even under this assumption, particles liberated from flocs near the bed are not likely to be scavenged by other flocs before returning to the near-bed region. The encounter rate coefficients for differential settling and turbulent shear are [*Hill and Nowell*, 1995]

$$(K_{ij})_{TS} = 0.16(d_i + d_j)^3(\varepsilon/\nu)^{1/2} \tag{2}$$

$$(K_{ij})_{DS} = \frac{\pi}{4}(d_i + d_j)^2|w_{sj} - w_{si}|. \tag{3}$$

The variables d_i and d_j refer to diameters of particles of types i and j, respectively; w_{si} and w_{sj} are the settling velocities of these particles; and ν is kinematic viscosity. Assuming that the particles liberated from flocs, which are called type i, are much smaller and slower sinking than the flocs themselves, which are called type j [*Sternberg et al.*, 1999], the expression for the aggregation timescale for a small particle being picked up by flocs becomes

$$\frac{1}{\left[0.16d_j^3(\varepsilon/\nu)^{1/2} + \frac{\pi}{4}w_{sj}d_j^2\right]n_j}. \tag{4}$$

To estimate an aggregation timescale, flocs are assumed to be ~1 mm in diameter (Figure 2) and to sink at 1 mm s^{-1} [*Hill et al.*, 1998]. Within the constant stress region of the boundary layer, ε varies as $u_*^3/\kappa z$ [*Heathershaw*, 1979], so the average ε sampled by a particle between the top of the wave boundary layer (≈2 cm) and the camera is u_* log(1.2/0.02)/(1.2κ). Assuming $u_* \approx 0.01$ m s^{-1}, the average dissipation rate is ~7 × 10^{-6} m^2 s^{-3}. Kinematic viscosity is set equal to 1.4 × 10^{-6} m^2 s^{-1}. The maximum number of flocs observed within the analysis box of any image was 119, so the maximal floc concentration was ~10^6 m^{-3}. With these inputs the aggregation timescale is ~900 s.

The shortest possible aggregation time in the bottom boundary layer at the Coastal Mixing and Optics site is an order of magnitude larger than the mixing timescale. Therefore floc size in the bottom boundary layer can be controlled by near-bed breakup in the wave boundary layer. In environments where sediment is more concentrated, however, aggregation may act fast relative to mixing. Fuller understanding of the interplay of floc breakup inside the wave boundary layer and floc reformation outside the wave boundary layer requires better constraint on rates of particle sticking and contact.

The view of controls on floc size in bottom boundary layers emerging from this work simplifies considerably the modeling of floc dynamics. If ε in the local vicinity of a floc controls its size, then a model of floc size and settling velocity must be coupled to a turbulence model. If, however, over a wide range of low to moderate energy levels, floc size does not depend strongly on ε, the need for coupled models of floc size and turbulence is reduced. Furthermore, at high energy levels the only relevant flow parameter for determining floc size is ε in the wave boundary layer.

The effect of floc breakup on the optical properties of a boundary layer remains to be investigated. Scatter and backscatter are dominated by small (<10 μm) particles [*McCave*, 1986; *Morel*, 1991]. If flocs preferentially scavenge certain particle sizes, thereby changing the particle size distribution of small, optically important particles, aggregated and disaggregated suspensions will have different spectra of scatter and backscatter. If, on the other hand, flocs are unbiased samplers of whatever particles are in suspension, they simply act as sources or sinks of optically important particles. Under this scenario, disaggregation will lead to an increase in scatter and backscatter, but the spectra of these optical properties will not change. In the future we plan to use multispectral data on absorption and attenuation gathered on the camera tripod [*Dickey et al.*, 1998] to assess the effect of disaggregation on inherent optical properties in the boundary layer.

5. Conclusion

Simultaneous observations of floc size, waves, and currents in a continental shelf bottom boundary layer demonstrate that turbulence plays a different role in limiting floc size than the one commonly accepted. Turbulence exerts a weaker than predicted influence on floc size at low-to-moderate energy, and at high energy, turbulence-induced stresses cause a dramatic greater than fourfold decrease in floc size. These observations lend support to the hypothesis that sinking-induced stresses on particles may limit floc size below some critical shear [*Adler and Mills*, 1979; *Adler*, 1979; *Hill et al.*, 1998].

Massive floc breakup occurs when the combined wave-current shear stress is >0.1 Pa. Incidence of floc breakup is not strongly correlated with periods of elevated current stress. These observations indicate that floc breakup occurring in the highly sheared near-bed region affect floc size throughout the boundary layer, thereby supporting the longstanding, untested hypothesis that the disaggregation rate is a function of maximal stress in a boundary layer. These observations also give waves a previously unrecognized, yet significant role in determining the transport rate of fine particles in continental shelf environments. When waves are large, floc size and settling velocity are small, so suspended material is distributed more evenly through the boundary layer than when waves are small. Because dispersal of suspended mass increases with distance from the bed, the more even distribution of mass caused by floc breakup increases sediment dispersal.

The breakup of flocs at combined wave-current stresses above 0.1 Pa formed particles or flocs too small to be resolved by the camera. Therefore it is not known from this study alone whether turbulence causes predictable changes in floc size at high stress. Resolution of this issue will require simultaneous deployment of instrumentation for measuring flow, flocs, and smaller particles (e.g., LISST-100) [*Agrawal and Traykovski*, this issue].

Acknowledgments. This research was supported by the U. S. Office of Naval Research contracts N00014-95-1-0420 (PSH) and N00014-95-1-0373 (JHT). We thank the captains and crews of R/V *Oceanus* and R/V *Knorr* for assistance in deploying and recovering the tripods and Liz Nickerson for her implementation of the image analysis code. B. Boudreau, A. Hatcher, E. Hildebrand, T. Milligan, L. Nickerson,

N. McCave, and J. Syvitski provided constructive criticism of earlier versions of this manuscript.

References

Adler, P. M., A study of disaggregation effects in sedimentation, *AIChE J.*, *25*, 487–493, 1979.

Adler, P. M., and P. M. Mills, Motion and rupture of a porous sphere in a linear flow field, *J. Rheol.* N. Y., *23*, 25–37, 1979.

Agrawal, Y. C., and P. Traykovski, Particles in the bottom boundary layer: Concentration and size dynamics through events, *J. Geophys. Res.*, this issue.

Alldredge, A. L., T. C. Granata, C. G. Gotschalk, and T. D. Dickey, The physical strength of marine snow and its implications for particle disaggregation in the ocean, *Limnol. Oceanogr.*, *35*, 1415–1428, 1990.

Berhane, I., R. W. Sternberg, G. C. Kineke, T. G. Milligan, and K. Kranck, The variability of suspended aggregates on the Amazon continental shelf, *Cont. Shelf Res.*, *17*, 267–286, 1997.

Campbell, D. E., and R. W. Spinrad, The relationship between light attenuation and particle characteristics in a turbid estuary, *Estuarine Coastal Shelf Sci.*, *25*, 53–65, 1987.

Dickey, T. D., G. C. Chang, Y. C. Agrawal, A. J. Williams III, and P. S. Hill, Sediment resuspension in the wakes of Hurricanes Edouard and Hortense, *Geophys. Res. Lett.*, *25*, 3533–3536, 1998.

Dunn, O. J., *Basic Statistics: A Primer for the Biomedical Sciences*, J. Wiley, New York, 1964.

Dyer, K. R., Sediment processes in estuaries: Future research requirements, *J. Geophys. Res.*, *94*, 14,327–14,399, 1989.

Eisma, D., A. J. Bale, M. P. Dearnaley, M. J. Fennessy, W. Van Leussen, M.-A. Maldiney, A. Pfeiffer, and J. T. Wells, Intercomparison of in situ suspended matter (floc) size measurements, *J. Sea Res.*, *36*, 3–14, 1996.

Grant, W. D., and O. S. Madsen, The continental-shelf bottom boundary layer, *Annu. Rev. Fluid Mech.*, *18*, 265–305, 1986.

Gustafsson, O., K. O. Buesseler, W. R. Geyer, S. B. Moran, and P. M. Gschwend, An assessment of the relative importance of horizontal and vertical transport of particle-reactive chemicals in the coastal ocean, *Cont. Shelf Res.*, *18*, 805–829, 1998.

Heathershaw, A. D., The turbulent structure of the bottom boundary layer in a tidal current, *Geophys. J. R. Astron. Soc.*, *58*, 395–430, 1979.

Heffler, D. E., J. P. M. Syvitski, and K. W. Asprey, The floc camera assembly, in *Principles, Methods and Applications of Particle Size Analysis*, edited by J. P. Syvitski, pp. 209–221, Cambridge Univ. Press, New York, 1991.

Hill, P. S., Reconciling aggregation theory with observed vertical fluxes following phytoplankton blooms, *J. Geophys. Res.*, *97*, 2295–2308, 1992.

Hill, P. S., Sectional and discrete representations of floc breakage in agitated suspensions, *Deep Sea Res. I*, *43*, 679–702, 1996.

Hill, P. S., Controls on floc size in the sea, *Oceanography*, *11*, 13–18, 1998.

Hill, P. S., and A. R. M. Nowell, Comparison of two models of aggregation in continental-shelf bottom boundary layers, *J. Geophys. Res.*, *100*, 22,749–22,763, 1995.

Hill, P. S., J. P. Syvitski, E. A. Cowan, and R. D. Powell, In situ observations of floc settling velocities in Glacier Bay, Alaska, *Mar. Geol.*, *145*, 85–94, 1998.

Hunt, J. R., Particle aggregate breakup by fluid shear, in *Estuarine Cohesive Sediment Dynamics*, edited by A. J. Mehta, pp. 85–109, Springer-Verlag, New York, 1986.

Jackson, G. A., Comparing observed changes in particle size spectra with those predicted using coagulation theory, *Deep Sea Res., Part II*, *42*, 159–184, 1995.

Kranck, K., and T. G. Milligan, Characteristics of suspended particles at an 11-hour anchor station in San Francisco Bay, California, *J. Geophys. Res.*, *97*, 11,373–11,382, 1992.

Li, X., and B. E. Logan, Collision frequencies of fractal aggregates with small particles by differential settling, *Environ. Sci. Technol.*, *31*, 1229–1236, 1997.

Logan, B. E., and D. B. Wilkinson, Fractal geometry of marine snow and other biological aggregates, *Limnol. Oceanogr.*, *35*, 130–136, 1990.

Luettich, R. A. J., J. T. Wells, and S.-Y. Kim, In situ variability of large aggregates: Preliminary results on the effects of shear, in *Nearshore and Estuarine Cohesive Sediment Transport, Coastal Estuarine Stud.*, vol. 42, edited by A. J. Mehta, pp. 447–466, AGU, Washington, D. C., 1993.

Marine Board, N. R. C., Dredging Coastal Ports: An Assessment of the Issues, Natl. Acad., Washington, D. C., 1985.

McCave, I. N., Vertical flux of particles in the ocean, *Deep Sea Res. Oceanogr. Abstr.* *22*, 491–502, 1975.

McCave, I. N., Mechanics of deposition of fine-grained sediments from nepheloid layers, *Geo Mar. Lett.*, *4*, 243–245, 1985.

McCave, I. N., Local and global aspects of the bottom nepheloid layers in the world ocean, *Neth. J. Sea Res.*, *20*, 167–181, 1986.

McCave, I. N., B. Manighetti, and S. G. Robinson, Sortable silt and fine sediment size/composition: Parameters for palaeocurrent speed and palaeoceanography, *Paleoceanography*, *10*, 593–610, 1995.

Miller, M. C., I. N. McCave, and P. D. Komar, Threshold of sediment motion under unidirectional currents, *Sedimentology*, *24*, 507–527, 1977.

Milligan, T. G., and K. Kranck, Electro-resistance particle size analyzers, in *Principles, Methods and Applications of Particle Size Analysis*, edited by J. P. M. Syvitski, pp. 109–118, Cambridge Univ. Press, New York, 1991.

Morel, A., Optics of marine particles and marine optics, in *Particle Size Analysis*, edited by S. Demers, pp. 141–188, Springer-Verlag, New York, 1991.

Ruiz, J., and A. Izquierdo, A simple model for the break-up of marine aggregates by turbulent shear, *Oceanol. Acta*, *20*, 597–606, 1997.

Russ, J. C., *The Image Processing Handbook*, 2nd ed., CRC Press, Boca Raton, Fla., 1995.

Sleath, J. F. A., Velocities and shear stresses in wave-current flows, *J. Geophys. Res.*, *96*, 15,237–15,244, 1991.

Snelgrove, P. V. R., and C. A. Butman, Animal-sediment relationships revisited: Cause versus effect, *Oceanogr. Mar. Biol.*, *32*, 111–177, 1994.

Sokal, R. R., and F. J. Rohlf, *Biometry*, 2nd ed., W. H. Freeman, New York, 1981.

Sternberg, R. W., I. Berhane, and A. S. Ogston, Measurement of size and settling velocity of suspended aggregates on the northern California continental shelf, *Mar. Geol.*, *154*, 43–54, 1999.

Stow, D. A. V., and A. J. Bowen, A physical model for the transport and sorting of fine-grained sediment by turbidity currents, *Sedimentology*, *27*, 31–46, 1980.

Trowbridge, J. H., On a technique for measurement of turbulent shear stress in the presence of surface waves, *J. Atmos. Oceanic Technol.*, *15*, 290–298, 1998.

Twichell, D. C., B. Butman, and R. S. Lewis, Shallow structure, surficial geology, and the processes currently shaping the bank, in *Georges Bank*, edited by R. H. Backus, pp. 31–38, MIT Press, Cambridge, Mass., 1987.

Voulgaris, G., and J. H. Trowbridge, Evaluation of the acoustic Doppler velocimeter (adv) for turbulence measurements, *J. Atmos. Oceanic Technol.*, *15*, 272–289, 1998.

Voulgaris, G., J. H. Trowbridge, W. J. Shaw, and A. J. Williams III, High resolution measurements of turbulent fluxes and dissipation rates in the benthic boundary layer, in *Coastal Dynamics 97*, edited by E. B. Thornton, pp. 177–186, Am. Soc. of Civ. Eng., Reston, Va., 1998.

P. S. Hill, Department of Oceanography, Dalhousie University, Halifax, Nova Scotia, Canada B3H 4J1. (paul.hill@dal.ca)

J. H. Trowbridge, Department of Applied Ocean Physics and Engineering, Woods Hole Oceanographic Institution, Woods Hole, MA 02543.

G. Voulgaris, Marine Science Program, Department of Geological Sciences, University of South Carolina, Columbia, SC 29208.

(Received April 13, 1999;
accepted November 10, 1999.)